Dual Nature of the Electronic Structure of the Stripe Phase

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INTRODUCTION

The existence and origin of charge-ordering in cuprates and its implication to high temperature superconductivity are at the heart of a great debate in physics[1]. Static one-dimensional (1D) charge ordering (stripe) along the [1,0] or [0,1] direction was first observed in $(La_{2-x-y}Nd_ySr_x)CuO_4$ (Nd-LSCO) system from neutron scattering[2], with complimentary evidence from other techniques. Similar signatures identified in $(La_{2-x}Sr_x)CuO_4$ (LSCO) and other high temperature superconductors point to the possible existence of stripes in these systems, albeit of dynamic nature. A key issue about this new electronic state of matter concerns whether the stripe phase is intrinsically metallic or insulating, given its spin and charge ordered nature, and more significantly, whether it is responsible for high temperature superconductivity. Understanding the electronic structure of the stripe phase is a prerequisite for addressing these issues and angle-resolved photoemission spectroscopy (ARPES) proves to be a powerful tool to provide these essential information. Here we report detailed ARPES results on the electronic structure of $(La_{1.4-x}Nd_{0.6}Sr_x)CuO_4$ with static stripes and a related superconductor $La_{1.85}Sr_{0.15}CuO_4$ (T_c=40K) with possible dynamic stripes. With high resolution ARPES spectra densely collected under various measurement geometries, we have identified in both systems the existence of spectral weight along the [1,1] nodal direction, where the superconducting gap is zero in *d*-wave pairing symmetry. The observation of nodal spectral weight, which is not compatible with ideal stripes along [1,0] or [0,1] direction, combined with the straight segments near $(\pi,0)$ and $(0,\pi)$ antinodal regions expected from 1D stripes[3], provides a complete view of the dual nature of the electronic structure of the stripe phase, revealing the competition of order and disorder in these systems.

EXPEIMENTAL

The experiment was carried out at beamline 10.0.1.1 of the Advanced Light Source[3]. The angular mode of the Scienta analyzer (SES-200) allows to measure an angle of ~14 degrees simultaneously, corresponding to ~1.1π in the momentum space for the 55eV photon energy we used (the unit of momentum is defined as 1/*a* with *a* being the lattice constant). The momentum resolution is 0.02π and the energy resolution is 16~20 meV. To check for polarization dependence and matrix element effect, we used various measurement geometries. For the data reported here, the sample was oriented so that the analyzer scan spans the diagonal direction. The mapping is realized *by rotating the analyzer* to change the polar angle while keeping the sample fixed. The electrical field vector E of the incident light is parallel to the sample surface. The $(La_{1.4-x}Nd_{0.6}Sr_x)CuO_4$ (x=0.10 and 0.15) and $(La_{2-x}Sr_x)CuO_4$ (x=0.15, T_c=40K) single crystals were grown using the traveling floating zone method which were characterized by various techniques. The sample was cleaved *in situ* in vacuum and measured at 15 K with a base pressure of $2\sim5X10^{-11}$ Torr.

RESULTS AND DISCUSSION

Fig. 1 shows the low energy excitations for both Nd-LSCO (x=0.15) (a) and $La_{1.85}Sr_{0.15}CuO_4$ (b) samples. There are two aspects involved in the electronic structure of both systems. The first is the straight segment near the $(0,\pi)$ and $(\pi,0)$ antinodal regions, as seen previously[3], even though the *a*-*b* plane of the samples were rotated 45 degrees with respect to each other. The feature is very robust and is seen under different measurement geometries, which appears to be a measure of the ordered nature of stripes. The second feature is the observation of spectral weight alnog the nodal direction and its associated Fermi surface, which are sensitive to doping and measurement geometry. This feature is likely a measure of deviation from ideal stripe case, which may be due to disorder or dynamic fluctuations.

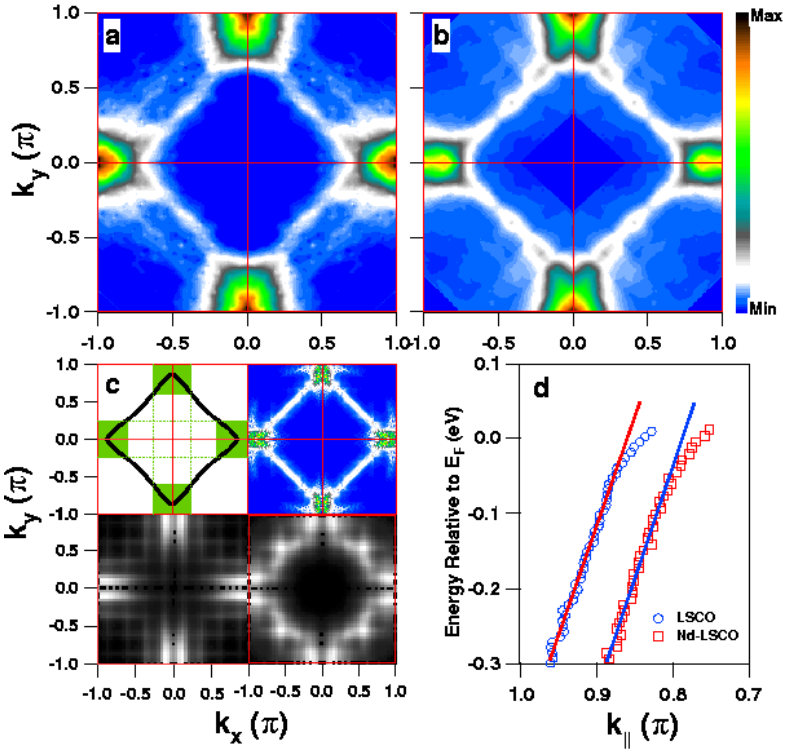

Figure 1. Measured low energy spectral weight of Nd-LSCO (x=0.15) (a) and LSCO (x=0.15) (b). The observed two features are schematically illustrated in (c) (upper-left panel): diamond-shaped nodal Fermi surface (black line) and 1D spectral confinements near (π,0) and (0,π) regions. The spectral weight patterns calculated from stripe fluctuation (upper-right panel)[4], from the site-centered stripe (lower-left panel) and bond-centered stripe (lower-right panel) [5] are also included in (c) for comparison. Fig. 3(d) shows the dispersion along the nodal direction for the Nd-LSCO and LSCO samples; a slope breakdown in the dispersion can be seen for both cases at nearly -50meV. The dispersion is obtained by fitting Momentum Distribution Curves (MDC) which show well-defined Lorentzian lineshape. The dispersion for Nd-LSCO is horizontally offset for clarity, with the two solid lines as guide to the eye.

A complete description of the electronic structure of the stripe phase needs to take both of the above two aspects into account: the straight segment near the antinodal region and the spectral weight near the nodal region with its associated Fermi surface. Fig. 1(c) schematically highlights these two features in the first Brillouin zone (upper-left panel). While it seems to be straightforward to associate the straight segments with stripes because of their 1D nature [3,4], the detection of spectral weight near the nodal region in the *static* stripe phase poses a new challenge to our understanding of this charge ordered state because the nodal spectral weight is expected to be suppressed in a simple stripe picture. The experimental question regarding the origin is whether they originate from another distinct phase or they are intrinsic properties of the same stripe phase. In the case of phase separation, this would mean that, besides stripes, there is another non-stripe metallic phase with a much higher carrier concentration, as estimated from the Luttinger volume of the diamond-shaped Fermi surface. As far as we know, there is little evidence of such a phase separation in Nd-LSCO and LSCO systems at the doping level discussed here.

The detection of nodal spectral intensity in the stripe system provides a clear distinction of the stripe physics from the ordinary 1D charge motion in a rigid 1D system. In the stripe context, the nodal Fermi surface may arise from disorder or fluctuation of stripes where the holes leak into the antiferromagnetic region [4]. Here disorder also induces the effect that the antiferromagnetic region may not be fully gapped when it becomes very narrow. The measured spectral weight in Fig. 1(a) and (b) for Nd-LSCO and LSCO, respectively, is similar to the one calculated based on such a disordered stripe picture (Fig. 1(c), upper-right panel)[4]. This also seems to be consistent with the trend that in LSCO the nodal spectral weight is more intense than that in Nd-LSCO because the stripes in the former are dynamic while they are static in the latter. However, the dispersion of the two systems (Fig. 1(d)) is very similar.

An alternative scenario to understand the two features in the stripe context is a possible coexistence of site- and bond-centered stripes[5]. As shown in Fig. 1(c), a combination of the calculated $A(k,E_F)$ patterns for the site-centered (lower-left panel) and bond-centered stripes (lower-right panel) [5] can reproduce the data. While the site-centered stripe shows little spectral weight near the nodal region, the bond-centered stripe is compatible with the nodal state. It is therefore tempting to associate the 1D straight segment to site-centered stripes and the nodal Fermi surface feature to bond-centered stripes. If this picture proves to be true, it would imply that, with increasing doping, bond-centered stripes are produced at the expense of site-centered stripes, and more bond-centered stripes may be generated as the

stripes become more dynamic. This seems to further suggest that the bond-centered stripes are more favorable for superconductivity than the site-centered stripes, a possibility remains to be investigated further.

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